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Climate change and its impacts on mountain glaciers during 1960–2017 in western China

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Abstract: Mountain glaciers are highly sensitive to climate change. In this paper, we systematically analyzed and discussed the responses of glaciers to climate change during 1960–2017 in western China by the methods of least squares and correlation analysis. Results show that the maximum temperature, minimum temperature, average temperature, and precipitation significantly increased in western China at the rates of 0.32°C/10a, 0.48°C/10a, 0.39°C/10a, and 11.20 mm/10a, respectively. However, the wind speed, hours of sunshine, snowfall, and snowy days displayed decreasing trends at the rates of –0.53 m/(s•10a), 3.72 h/10a, –2.90 mm/10a, and –0.10 d/10a, respectively. The annual percentage of glacier area decreased by approximately 0.42%, and the average glacier area decreased by 2.76 km²/a. Meanwhile, glacial shrinkages were greater in the Altay Mountains, Tanggula Mountains, and Qilian Mountains than in the other mountainous regions. Glacier accumulation decreased while melt volume increased at a rate of 2.7×10^4 m³/a. The area of melt volume was 1.3 times that of the glacier accumulation area. The glacier mass balance (GMB) decreased substantially at a rate of –14.0 mm/a, whereas the equilibrium line altitude (ELA) showed an increasing trend at a rate of 0.5 mm/a. After 1997, the mass was smaller than –500.0 mm, indicating a huge loss in glaciers. Furthermore, relationships between ELA and GMB and various climatic factors were established. Temperature and precipitation demonstrated a significantly negative correlation, whereas wind speed and snowy days had significantly positive correlations with GMB. Snowy days also exhibited a remarkably negative correlation with ELA. The strong warming trend and less snowy days were thought to be the main factors leading to glacial melting, whereas the increase in precipitation, and reductions of sunshine hours and wind speed might slow glacial melting.

Keywords: temperature; precipitation; climate trend; glacier variation; impacts; western China

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1 Introduction

Glaciers and snow are the main components of the cryosphere, and mountain glaciers are highly sensitive to climate elements such as temperature, precipitation and wind (Pederson et al., 2004; Liu et al., 2006; Yao et al., 2012; Zhao et al., 2016). Global warming exerts significant impacts on glacier mass accumulation and ablation intensity and can cause advances or retreating in the

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glacier area (Nie et al., 2010; Xiao, 2011; Bai et al., 2012; Duan et al., 2017; Palerme et al., 2017). The modern glacier area across the world is thought to cover approximately 29×10^6 km^2, of which 4.6377×10^4 glaciers with a total glacier area of 5.9425×10^4 km^2 are distributed in China (Wu and Li, 2004; Shi, 2005; Liu et al., 2016; Manton et al., 2017). The accelerating shrinkage of glaciers can affect solid water resources and sea level change (Yao et al., 2004; Lu et al., 2005; Bolch, 2007; Qin and Ding, 2009; Zhang et al., 2009; Li et al., 2012; Wang et al., 2015). Therefore, scholars worldwide have paid great attention to glacier variation (Radić and Hock, 2010; Grinsted, 2013; Mög et al., 2013). In recent years, remote sensing image and satellite data (Yang et al., 2005; Li et al., 2011; Frey et al., 2012) as well as glacier survey catalog data (Zhang et al., 2011; Frey et al., 2012; Liu et al., 2015) have been widely used in research on glacier area change and glacier mass balance (GMB) change. The impact of climate change on glaciers has been simulated using different methods (Wang et al., 2011a; Wang et al., 2013; Zhu et al., 2014; Duan et al., 2017). For example, with regard to global warming, many observations have demonstrated that global glaciers appear to be retreating in many parts of the world, such as northern Tianshan Mountains (Kazakhstan/Kyrgyzstan; Bolch, 2007), the western Himalaya Mountains (Frey et al., 2012), and the mountain areas of Central Asia (Kutuzov and Shahgedanova, 2009), resulting in a lower volume of glaciers throughout the world (Grinsted, 2013). Glaciers in China are also experiencing varying degrees of rapid shrinkage and melting (Liu et al., 1998, 2006; Yao et al., 2004; Kang et al., 2007; Du et al., 2008; Duan et al., 2009; Shi et al., 2010; Wang et al., 2012; Zhang et al., 2013). A few studies have examined the relationship between climate change and GMB along with changes in glacier length during 1970s–1990s; for example, Klok and Oerlemans (2004) used 17 length records of glaciers in Europe to retrieve climate reconstructions. Other researchers studied glacier sensitivity to climate warming (Ye et al., 2001; Yang et al., 2005; Liu et al., 2006; Wang et al., 2008), while Pederson et al. (2004) analyzed the driving force of the decadal scale climate on glaciers.

Although considerable research has investigated climate change and glacier variation with valuable results, most studies have focused on short-term data in a single glacier using simple methods. Accordingly, the findings of such work are limited. Furthermore, much scholarship has concerned the impact of climate change on individual glaciers and glaciers in tributaries, qualitatively explaining the glacial response to climate. By comparison, glaciers and climate have been less studied comprehensively overall. The impact of multiple meteorological factors on glaciers is particularly poorly studied, and the relationships between glacier variation and climate change need further study. Therefore, in this paper, a long period of meteorological factors (since the 1960s) and different glacier sequences are selected using least squares, permutation, and related regression methods. Longitudinal changes in climate and the response of typical glaciers in western China are presented. This study may serve as the basis for further evaluation of climate change and glacier variation.

2 Materials and methods

2.1 Meteorological data

Western China is located between 26°00′12″N–47°51′36″N and 73°18′52″E–104°46′59″E. It begins at the Pamir Plateau in the west, crosses the Hengduan Mountains in the east, extends from the southern margin of the Himalaya Mountains to the north, and reaches the Kunlun Mountains and Qilian Mountains in the north. Daily meteorological data used in this study were obtained from the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). Eight meteorological parameters were selected, including maximum temperature, minimum temperature, average temperature, precipitation, snowfall, wind speed, sunshine hours, and snowy days in western China from 1960 to 2017. The annual average values of the eight meteorological parameters during 1960–1990 were used as the standard values to calculate annual anomalies. To make the analysis results more reliable, we selected 78 weather stations (Fig. 1) near the studied glacier regions in western China to obtain related meteorological

data for a comparison.

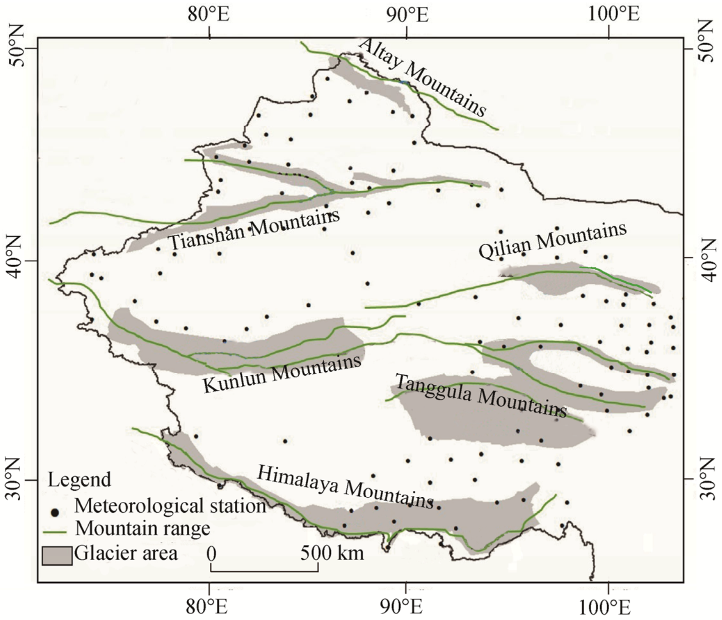

Fig. 1 Distribution of meteorological stations and glacier areas in western China

Monthly data were obtained from daily data, and the annual average value was derived from the mean of every month. Anomalies avoided potential biases caused by missing data. The least squares method was applied to calculate the linear trends in meteorological parameters. A positive value indicates the increase rate in climatic factors, a negative value represents the reduction rate in climatic factors, and the absolute value denotes the intensity of change.

Meteorological parameters often appear as a series of rising or falling trends and change in spatial distribution patterns. It generally can be considered as a linear regression of time, and the linear propensity value was estimated by least squares:

$$Q=[\sum_{i=1}^{n}x_i t_i-1/n(\sum_{i=1}^{n}x_i)(\sum_{i=1}^{n}t_i)]/[\sum_{i=1}^{n}t_i^{\,2}-1/n(\sum_{i=1}^{n}t_i)^2], \quad (1)$$

where x_i is the single climatic factor i; t_i is the time (year); n is the number of samples; and Q is the trend value, in which Q>0 indicates an increasing trend, otherwise, a declining trend.

2.2 Glacier data

Mountain glaciers are widely distributed in western China (Wu and Li, 2004; Shi, 2008; Liu et al., 2015). Small glaciers (with an area <1 km^2), large glaciers (with an area >10 km^2), and huge glaciers (with an area >100 km^2) account for 20.0%, 37.6%, and 10.4% of the total glacier area, respectively (Shi et al., 2010). In this study, the area of 2.4×10^4 km^2 for typical glaciers was collected, accounting for 45.3% of the total glacier area in western China. This research refers to the following seven typical glacier areas: Altay Mountains (AMG), Tianshan Mountains (TMG), Qilian Mountains (QMG), west Kunlun Mountains (WKMG), east Kunlun Mountains (EKMG), Tanggula Mountain (TGMG), and Himalaya Mountains (HMG) (Fig. 1). The data of glacier area were obtained from long-term ground observations, glacier inventory, and remote sensing data during 1960–2009 along with related documents about glacier areas published throughout the 1960s–1970s until the 2000s (Table 1). Long-term detailed observation data for ELA (equilibrium line altitude) were available, and GMB (glacier mass balance) data were obtained from Urumqi Glacier No. 1 at Tianshan Mountains. Although glaciers are not evenly distributed in different drainage basins, the data sources at different spatial and temporal scales are helpful for estimating large-scale glacier variation. An area-based weighted method (Wang et al., 2011b) was considered

in this study to estimate glacier area changes. The study period was unified via interpolation for the variation of glacier area per unit of time to ensure every reference remained stable. The permutation method was used to calculate the glaciers for each subsequent period. At the same time, we analyzed and explored the response of glaciers to climatic factors based on the correlation regression method. Annual variation of glacier area is defined as follows:

$$AAC = \sum_{i=0}^{n} W \times \frac{\sum_{j=0}^{n} \frac{\Delta A_{ij}}{\Delta t_{ij}}}{\sum_{j=0}^{m} \left(A_{oij} + \frac{\Delta A_{ij}}{\Delta t_{ij}}(t_{oij} - t_o)\right)}, \tag{2}$$

$$W = \frac{A_i'}{A'}, \tag{3}$$

where AAC is the annual variation of glacier area (%); n is the number of samples; i is the number of 2nd-grade drainage basin; W is the weight of glacier area; j is the number of 3rd-grade drainage basin; A_{oij} is the initial status of the glacier area (km^2); ΔA_{ij} is the variation in glacier area (km^2); Δt_{ij} is the number of years; t_o and t_{oij} are the initial year and end year, respectively; A_i' is the area of glaciers in the drainage basin (km^2); and A' is the total glacier area (km^2).

Table 1 Data sources of glacier areas in western China

Study region	Reference	Period
AMG	Youyi area (Bai et al., 2012)	1959–2009
	Burqin River Basin (Wang et al., 2011a, b; Bai et al., 2012; Yao et al., 2012)	1959–2008
TMG	Headwaters of the Urumqi River (Wu et al., 2011; Wang et al., 2012; Li et al., 2013)	1960–2010
	Kuytun River Basin (Jiao et al., 2009)	1964–2006
	Mt. Tuomuer Region (Nie et al., 2010; Wang et al., 2010)	1964–2009
	East watershed of Mt. Tuomuer (Xie et al., 2006; Yao et al., 2009)	1962–2009
	Bogda-peak region (Wu et al., 1983; Wang, 1991; Wu et al., 2011)	1960–2009
	Kukesu River (Gao et al., 2011)	1963–2004
QMG	Lenglong Ling Mountain (Zhang et al., 2010)	1970–2009
	Yeniugou River watershed (Yang et al., 2007)	1956–2003
	Shule Nan Mountain (Zhang et al., 2011)	1970–2006
	Beidahe River Basin (Yan et al., 2012)	1956–2003
	Laohugou Basin (Sun et al., 1981; Du et al., 2008; Zhang et al., 2013)	1957–2009
	Beidahe River Basin (Yan et al., 2012)	1956–2003
WKMG	West Kunlun Mountains (Li et al., 2013)	1976–2010
	Karakorum Mountains (Xu et al., 2016)	1978–2015
EKMG	A'nyêmaqên Mountain (Wang et al., 2015)	1992–2010
	Malan Mountain (Jiang et al., 2012)	1973–2010
TGMG	Nyainqêentanglha Range (Kang et al., 2007; Shangguan et al., 2008)	1970–2000
	Ngangla Ringco Catchment (Ye et al., 2006; Ye et al., 2007; Zhang et al., 2012)	1973–2010
	Nam Co Basin (Lu et al., 2005; Wu et al., 2007; Chen et al., 2009)	1970–2008
	Yurungkax River (Shangguan et al., 2004)	1970–2001
HMG	Lhozhag region (Qin, 1999; Shi, 2005; Zhang et al., 2009; Li et al., 2012)	1980–2007
	Pum Qu Basin (Qin, 1999; Jin et al., 2004; Shi, 2005; Zhang et al., 2009)	1970–2001

Note: AMG, Altay Mountains; TMG, Tianshan Mountains; QMG, Qilian Mountains; WKMG, west Kunlun Mountains; EKMG, east Kunlun Mountains; TGMG, Tanggula Mountains; HMG, Himalaya Mountains.

3 Results

3.1 Climate trends

Totally 7, 32, 21, 9, 24, 10, and 19 meteorological stations were respectively selected in the AMG, TMG, QMG, WKMGG, EKMG, TGMG, and HMG areas to calculate climate data and analyze climate change and anomalies and linear trends. Figure 2 displays the anomaly variations of climatic factors in seven regions of typical glaciers in western China. The annual average temperature and average annual precipitation had generally demonstrated an increasing trend over the past 57 years. The increase rates of average temperatures in the AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas were 0.38°C/10a, 0.31°C/10a, 0.33°C/10a, 0.26°C/10a, 0.37°C/10a, 0.63°C/10a, and 0.47°C/10a, respectively. The precipitation in these areas increased at the rates of 12.80, 12.90, 10.39, 17.84, 8.09, 5.33, and 21.70 mm/10a, respectively. The average temperature initially decreased during 1960–1969 and then presented a steadily increasing trend during 1970–1984, followed by a remarkable rise after 1985. Precipitation first increased slightly during 1960–1971, then substantially fluctuated before 2000, and finally exhibited an obvious increase after the start of the 21st century. However, before 1984 in the AMG area, the precipitation trend was opposite to the temperature change; and after 1999 in the TMG area, precipitation showed a significantly decreasing trend.

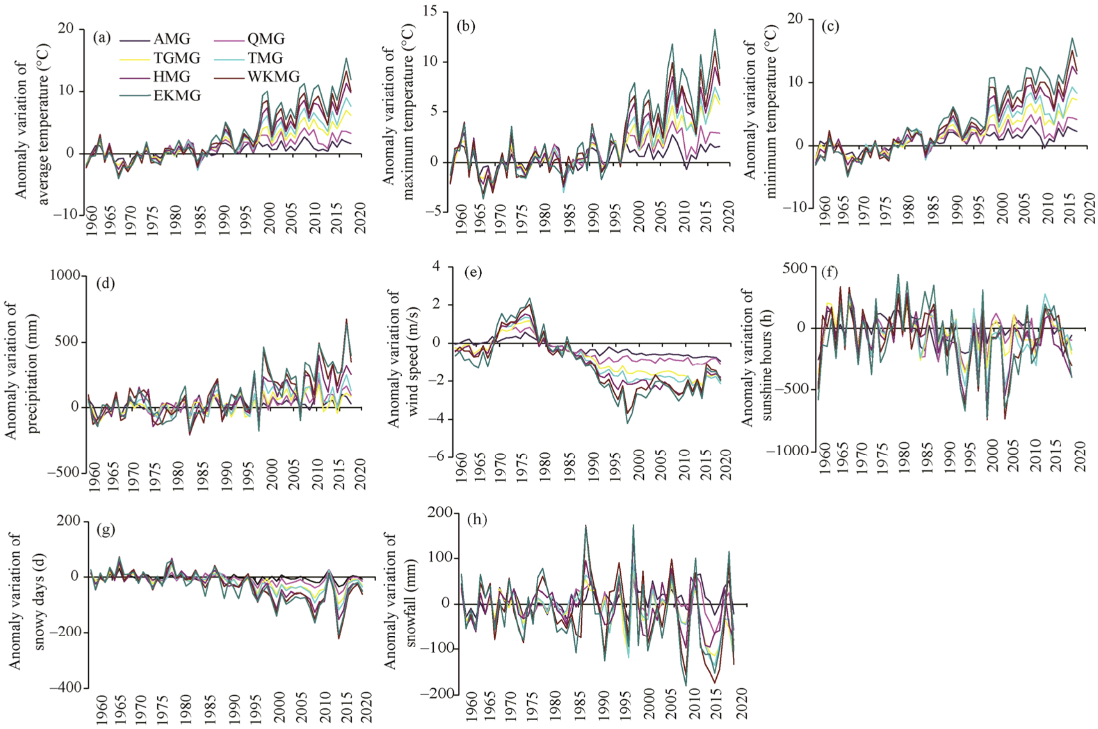

Fig. 2 Anomaly variations of climatic factors in different areas of western China during 1960–2017. AMG, Altay Mountains; TMG, Tianshan Mountains; QMG, Qilian Mountains; WKMG, west Kunlun Mountains; EKMG, east Kunlun Mountains; TGMG, Tanggula Mountains; HMG, Himalaya Mountains. The abbreviations are the same as in Figures 3 and 4.

The maximum temperature in the AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas generally showed a marked increase at the rates of 0.32°C/10a, 0.12°C/10a, 0.29°C/10a, 0.21°C/10a, 0.29°C/10a, 0.59°C/10a and 0.37°C/10a, respectively, and the increase rates of minimum temperature were 0.54°C/10a, 0.35°C/10a, 0.34°C/10a, 0.37°C/10a, 0.45°C/10a, 0.68°C/10a, and 0.65°C/10a, with the largest increases in the AMG, TGMG, and HMG areas and the smallest variations in the QMG area. The maximum and minimum temperatures first decreased throughout 1960–1970, and then presented a steadily increasing trend before 2000 and

an obvious increase thereafter.

Wind speed and snowy days each showed a generally decreasing trend. The trend rates of wind speed in the AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas were –0.19, –0.06, –0.06, –0.02, –0.04, –0.28, and –0.06 m/(s•10a), respectively. The wind speed increased during 1960–1975, then decreased considerably during 1976–1990 and slightly fluctuated thereafter. The trend rates of snowy days were –1.69, –1.58, –3.35, –3.65, –0.66, –6.22, and –7.37 d/10a, respectively. In the AMG, TMG, QMG, GMG, and HMG areas, hours of sunshine decreased at the rates of –9.58, –5.41, –0.87, –5.59, and 26.51 h/10a, but increased at the rates of 12.02 and 10.29 h/10a in the EKM and TGMG areas, respectively. Contrarily, snowfall demonstrated fluctuating variations in the AMG, TMG, QMG, WKMG, EKMG, TGMG, and HMG areas with the rates of 4.81, 0.54, –0.47, –5.27, 0.49, –13.75, and 3.23 mm/10a, respectively. Snowfall increased in the AMG area, TGMG, and EKMG areas but decreased in the other three regions.

Overall, temperature and precipitation each showed a substantially increasing trend, especially in the AMG and HMG areas, whereas other meteorological parameters including wind speed, sunshine hours, snowy days, and snowfall showed slightly decreasing trends. The average temperature, maximum temperature, minimum temperature, and precipitation in the northwest region have appeared to increase over the past 57 years at the rates of 0.39°C/10a, 0.32°C/10a, 0.48°C/10a, and 11.2 mm/10a, respectively. Snowfall, wind speed, sunshine hours, and snowy days declined at the rates of –2.09 mm/10a, –0.30 m/(s•10a), –3.72 h/10a, and –0.10 d/10a, respectively. Compared with the national temperature and precipitation, increases were higher in western China than in China as a whole (Liu et al., 2015; Tan et al., 2017; Zhang et al., 2017), indicating that climate conditions in the five glacier regions experienced a wetting and warming process over the past 57 years.

The standard index of climatic factors is computed in Figure 3. Temperature and precipitation exhibited a substantial increasing variability, whereas other meteorological parameters (e.g., snowy days and snowfall) showed slight declines. The greatest in minimum temperature and wind speed was in the TGAG area; and precipitation and snowy days demonstrated the greatest variability in the TMG and TGMG areas. Snowfall and sunshine hours had a relatively large scope in the TGMG and HMG areas, as did wind speed in the ATG area.

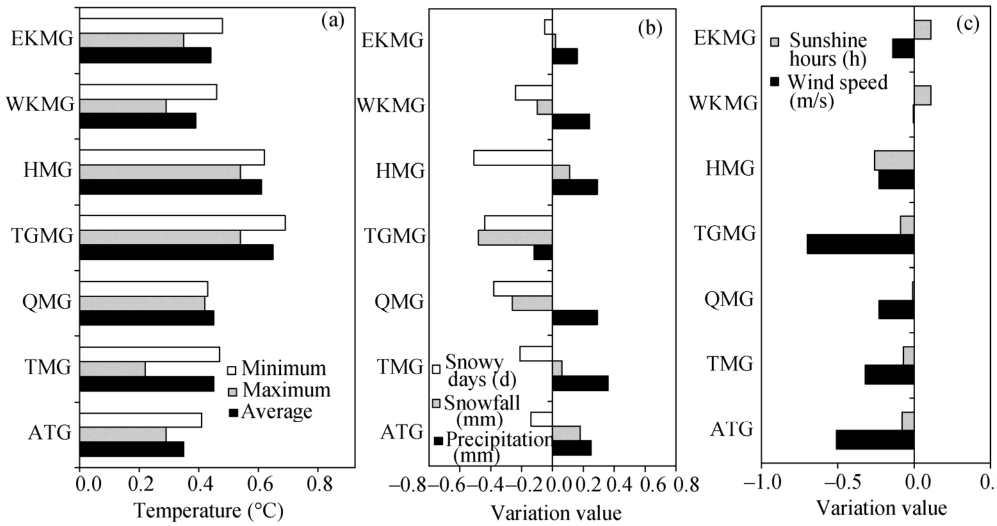

Fig. 3 Variation of climatic factors in western China during 1960–2017

3.2 Glacier variation and response to climate change

According to the calculation, the variation rates of the average glacier area in the AMG, TMG, TGMG, QTG, and HMG areas were –2.30, –4.70, –0.44, –2.75, and –3.61 km^2/a, respectively. The average glacier area of these five regions retreated by 0.56%/a or 2.76 km^2/a in total during 1960–2009. As shown in Figure 4, the glacier areas in the five regions all retreated rapidly.

Especially in the TGMG and AMG areas, the percentage of annual variation in area retreated most noticeably.

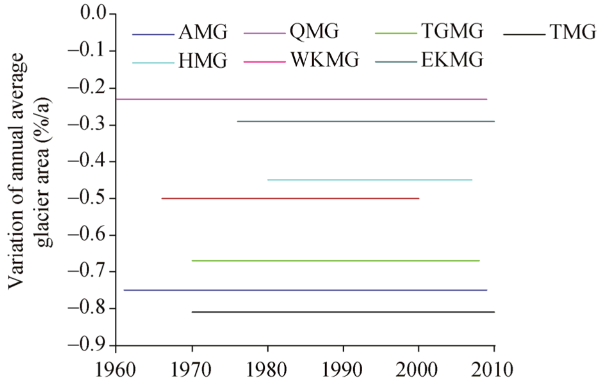

Fig. 4 Variation of annual average glacier area in different areas of western China during 1960–2010

Figure 5 displays the variations in GMB and ELA. The GMB substantially decreased at a rate of –14 mm/a, whereas the ELA exhibited an increasing trend at a rate of 0.5 mm/a. Especially after 1984, the mass balance essentially remained in a negative state; notably, it was less than –500.0 mm after 1997, indicating a great loss. Figure 6 indicates that the annual GMBs at various altitudes sharply decreased during 1960–2009. The higher the altitude, the greater the reduction, peaking at altitudes >4200 m. Figure 7 shows that glacial accumulation decreased while melt volume increased at a rate of 2.7×10^4 m^3/a. The area of melt volume was 1.3 times that of the glacier accumulation area.

Figure 8 displays the correlation coefficients of the climatic factors with GMB and ELA. The contributions of climatic factors to the variation of glacier areas differed: the temperature and precipitation demonstrated significantly negative correlations with GMB, whereas snowy days and wind speed showed significantly positive correlations with GMB (i.e., a correlation coefficient above 0.3387). Snowy days and ELA exhibited significantly negative correlations with a correlation coefficient of –0.3763 (at a confidence level of 99%). The relationships between other climatic factors and either ELA or GMB were relatively poor.

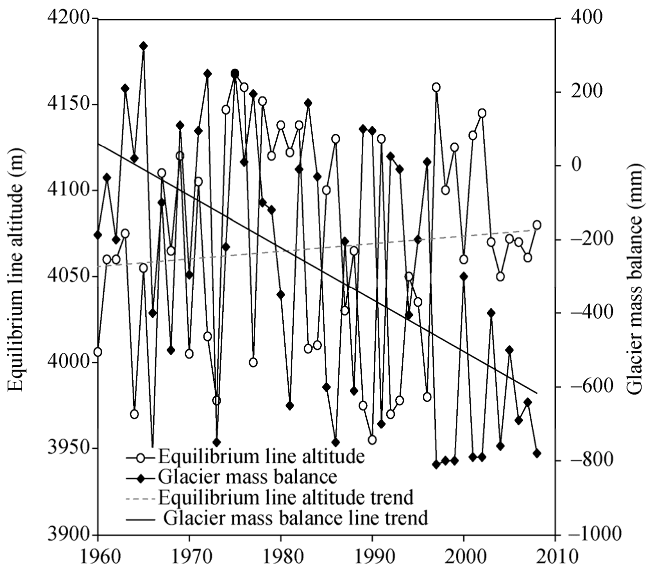

Fig. 5 Variations of glacier mass balance and equilibrium line altitude during 1960–2010

Figure 9 illustrates the relationships of GMB and ELA with climatic factors. GMB exhibited polynomial relations with wind speed, temperature, precipitation, and snowy days, whereas ELA

showed a linear relation with snowy days. To analyze the sensitivity of GMB and ELA to climate changes, we established the linear relationships of climatic factors with ELA and GMB as follows:

$$\mathrm{GMB}=-316.34T_{\min}-651.84, \tag{4}$$

$$\mathrm{GMB}=-313.10T_{\max}-843.27, \tag{5}$$

$$\mathrm{GMB}=-3.68P+430.87, \tag{6}$$

$$\mathrm{GMB}=810.40v-2144.00, \tag{7}$$

$$\mathrm{GMB}=21.52\mathrm{SD}-1592.10, \tag{8}$$

$$\mathrm{ELA}=-3.37\mathrm{SD}+4272.00, \tag{9}$$

where GMB is the glacier mass balance (mm); ELA is the equilibrium line altitude (m); and $T_{\min}$, $T_{\max}$, P, v, and SD are the minimum temperature (°C), maximum temperature (°C), precipitation (mm), wind speed (m/s), and snowy days (d), respectively.

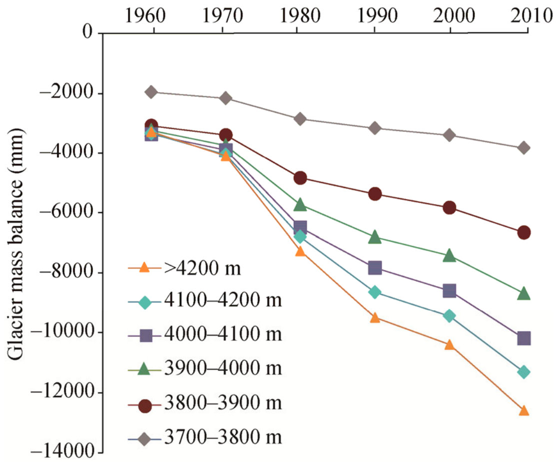

Fig. 6 Variations of glacier mass balance at different altitudes during 1960–2010

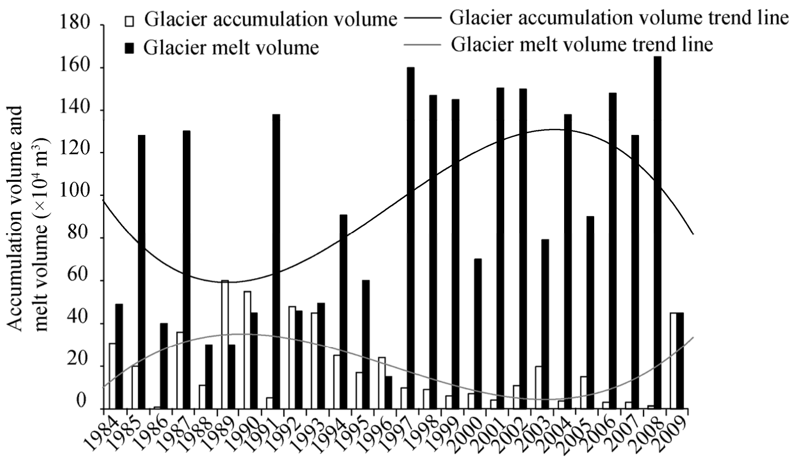

Fig. 7 Variations of glacier accumulation volume and melt volume during 1984–2009

When the minimum and maximum temperatures increased by 1.0°C, the GMB decreased by approximately 316.0 and 313.0 mm, respectively, around 40.0 mm smaller than the reference results (Pu et al., 2005). When the precipitation increased by 100.0 mm, the GMB decreased by approximately 368.0 mm, about 1.7 mm higher than the reference results (Pu et al., 2005). When the velocity decreased by 1.0 m/s, the GMB decreased by about 810.0 mm. When the number of snowy days decreased by 10.0 d, the GMB decreased by around 215.0 mm, whereas ELA increased by about 33.7 m. These results indicate that the GMB was more sensitive to temperature

and wind speed than to the other climatic factors.

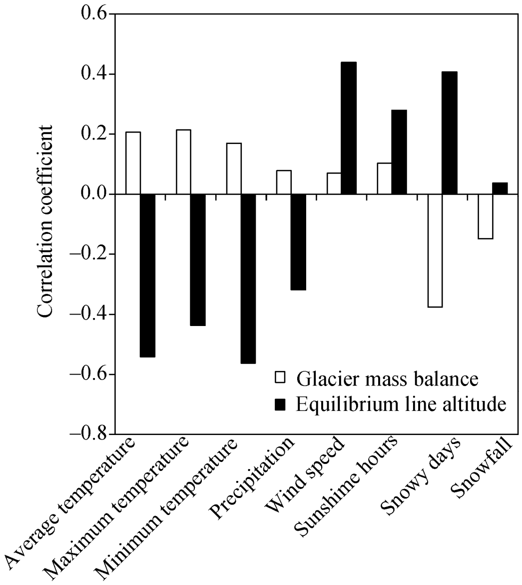

Fig. 8 Correlation coefficient of glacier area and climatic factors

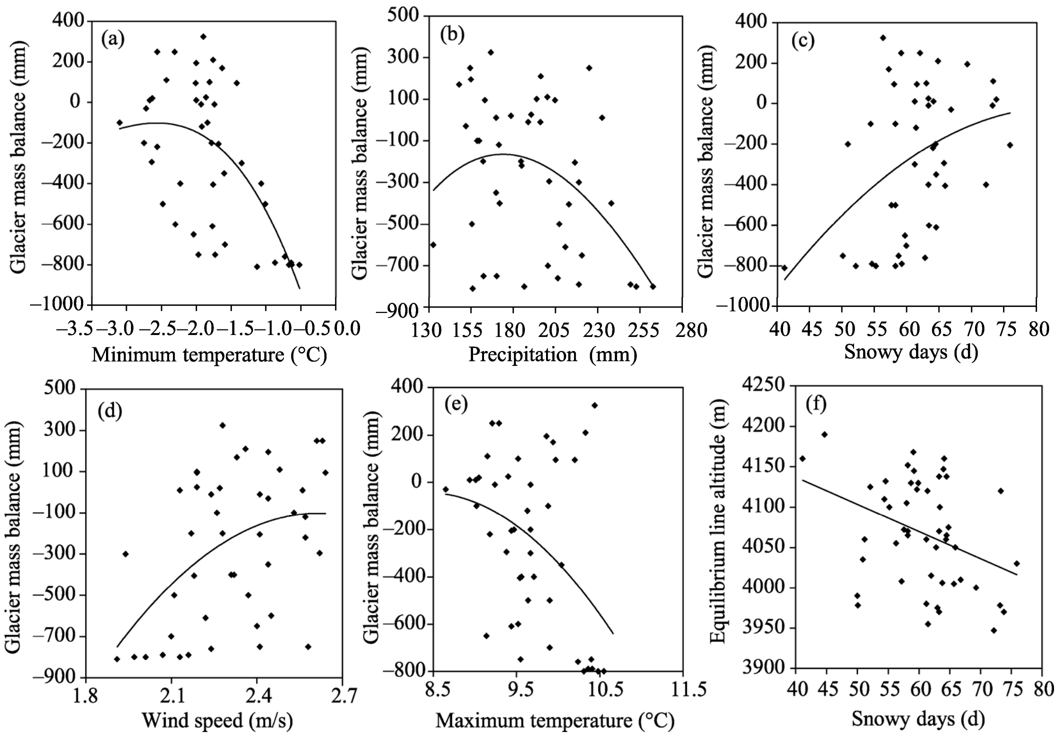

Fig. 9 Relationships of glacier mass balance (a–e) and equilibrium line altitude (f) with climatic factors

4 Discussion

In all regions included in this study, the maximum temperature, minimum temperature, and average temperature during 1960–2017 showed increasing trends of 0.12°C/10a–0.59°C/10a, 0.23°C/10a–0.65°C/10a, and 0.26°C/10a–0.63°C/10a, respectively. Precipitation increased at the rates of 80.09–21.70 mm/10a in all areas except for the TGLM. These findings are mostly

consistent with extant literature on climate trends and glacial change (Zhang et al., 2011; Guo et al., 2015; Li et al., 2016). However, the estimated value of the percentage of annual variation in area in this present study is 4% higher than previous results, and the rates of climate trends are lower than those in existing literatures (Liu et al., 2006; Wang et al., 2011a; Li et al., 2011; Yao et al., 2012). These differences may be due to different time scales and methods. On the whole, these results further reveal the wide range of climate and glacial trends in the entire western region of China. Regional wind speed and snow days decreased at the rates of 0.06–0.29 m/(s•10a) and 0.66–6.32 d/10a, respectively. Sunshine hours also decreased at the rates of 0.87–26.51 h/10a in all areas except for WKM and EKM areas. These climate factors also had varying degrees of influence on glaciers.

Climate factors have caused glaciers to retreat in different regions of western China—especially temperature, precipitation, and wind speed, which are significantly related to GMB in the TMG area. In this study, estimates indicate that every 1.0°C increases in minimum temperature and maximum temperature caused GMB to decrease by approximately 316.0 and 313.0 mm, respectively. Every 100.0 mm increase in precipitation led to a 368.0 mm increase in GMB, while every 1.0 m/s decrease in wind speed induced an 810.0 mm decrease in GMB. Increasing snowy days caused GMB to increase 215.0 mm every 10.0 d. Pu et al. (2005) found that every 1.0°C and 100.0 mm increases in temperature and precipitation created corresponding GMB increases of approximately 356.0 mm/°C and 366.3 mm/100.0 mm, respectively. Although present estimates differ from those of that study, both sets of results confirm that climate change affects glaciers; and the discrepancy may be due to climate change and statistical spatial and temporal scale differences.

Physical explanations also apply in these trends. Previous research has suggested that temperature increases can cause substantial losses of GMB in different regions (Jiang et al., 2010; Duan et al., 2017). Chen et al. (2015) proposed that the retreat rate of glaciers in the central Qilian Mountains increased during 1956–2011, while the ice surface elevation decreased. Zhu et al. (2017) examined data from climate experiments and gravity recovery in Central Asia and found periodic fluctuations in GMB, indicating GMB is significantly correlated with precipitation. Wei et al. (2015) also suggested that glaciers had experienced rapid mass loss in China's Altay Mountains. Similarly, Kononova et al. (2015) pointed out that atmospheric circulation and precipitation in summer have influenced GMB in the TMG. Others reported that the correlation between glaciers, precipitation, and temperature was significant (Wang et al., 2011a; Liu et al., 2006). In summary, variations of climatic factors affect glaciers via two main mechanisms: (1) temperature significantly influences glacial melting, precipitation greatly influences glacial accumulation, and both of them determine the nature, development, and evolution of glaciers (Jin et al., 2004; Shi, 2008, Wang et al., 2008); and (2) the sensitivity of the glacier area to climate change, which is closely related to glacier size. Smaller glaciers were more sensitive to climate warming than larger ones (Ye et al., 2001; Li et al., 2011; Wang et al., 2011b). The present research confirms and extends the above findings but has some differences. In this study, when the temperature increased by 1.0°C, the GMB loss could be offset by a 20.0% increase in precipitation, approximately 12.0% higher than that reported in the literature (Liu et al., 1998; Pu et al., 2005; Wang et al., 2011a). This result could be attributed the relative longer time series of meteorological parameters and glaciers' data, and the plenty of data sites. Moreover, this study revealed that snowy days, sunshine hours, and wind speed showed a decreasing trend during the study period, which caused a GMB increase. Specifically, the maximum shrinkage of the glacier area in the AM and TAM areas corresponded to the greatest temperature rise and wind speed increase as well as fewer snowy days and less precipitation. These results further demonstrate that glacial melting is driven by multiple climatic factors.

The above analysis indicates that, GMB is most sensitive to temperature changes among all climatic factors. When the temperature increases, glaciers become thinner and their area gradually shrinks, leading to a rise in the snow line and an increase in the ELA. However, precipitation

plays a different role in GMB. Furthermore, reduced sunshine hours and slower wind speed may inhibit glacial ablation. Smaller glaciers are more sensitive to climate warming than larger ones. As a result, shrinkage of the glacier area is actually affected by the combination of many meteorological parameters and physical features of glaciers.

5 Conclusions

The maximum temperature, minimum temperature, and average temperature in all regions presented significantly increasing trends, and the maximum rate of increase in the NTM area was 0.61°C/10a. Precipitation also showed an increase in most areas except for a reduction of –5.33 mm/10a in the NTM; and the greatest increase was 21.70 mm/10a in the HMG area. Snowfall, wind speed, sunshine hours, and snowy days exhibited decreasing trends. Wind speed decreased by up to 0.19 and 0.28 m/(s•10a) in the AMG and TGMG areas, respectively. The variation ranges of temperature, precipitation, and wind speed were greatest in the AM, NTM, and HMG areas compared with other areas.

The glaciers have rapidly retreated during the past 57 years in western China. The average area variation of glaciers was largest in the TMG and HMG areas, and the annual percentage of glacier area intensively retreated in the AMG and TGMG areas. Annual GMB decreased sharply and the melt volume of glacier was 1.3 times that of the glacier accumulation, whereas ELA showed an increasing trend. After 1997, the glacier mass balance was smaller than –500.0 mm and reflected a huge loss.

Temperature and precipitation significantly demonstrated negative correlations, whereas wind speed and snowy days had significantly positive correlations with GMB over the past 57 years. Glacier mass balance was more sensitive to temperature and wind speed than to other climatic factors. The pronounced warming trend and fewer snowy days may be the driving factors behind glacial retreat. Although precipitation increased, a decline in sunshine hours and wind speed may have slowed glacial melting.

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